

A Path to Freeform Optics

Kyle Fuerschbach

University of Rochester

Jannick Rolland

University of Rochester

Kevin Thompson

Synopsys

Role of Non-Symmetric/Freeform Surfaces in Optical Systems Design

- Packaging is a driving constraint during optical design
- Non-symmetric surfaces provide new degrees-of-freedom for achieving shrinking space requirements
 - Minimize number of elements
 - Tilted/Decentered geometries

Deployment of Optical Systems

	Spheres	Symmetric Aspheres	Off-Axis Conics	ϕ Polynomials	Freeform Shapes
Surface Shape	1890	1960s-70's*	1980's	2000	Active Research
Optical Design	1890	60s-70s	Late 90's (DARPA)	Active Research	Active Research
Surface Fabrication	1890	2005*	1980's	2007	Active Research
Surface Testing	Evolution	Active Research	Active Research	Active Research	Future Research
Telescope Assembly	Evolution	Evolution	Active Research	Active Research	Future Research

*Recently (2005) it has been demonstrated that power series aspheres are mathematically unstable and new surface formulation has been proposed.

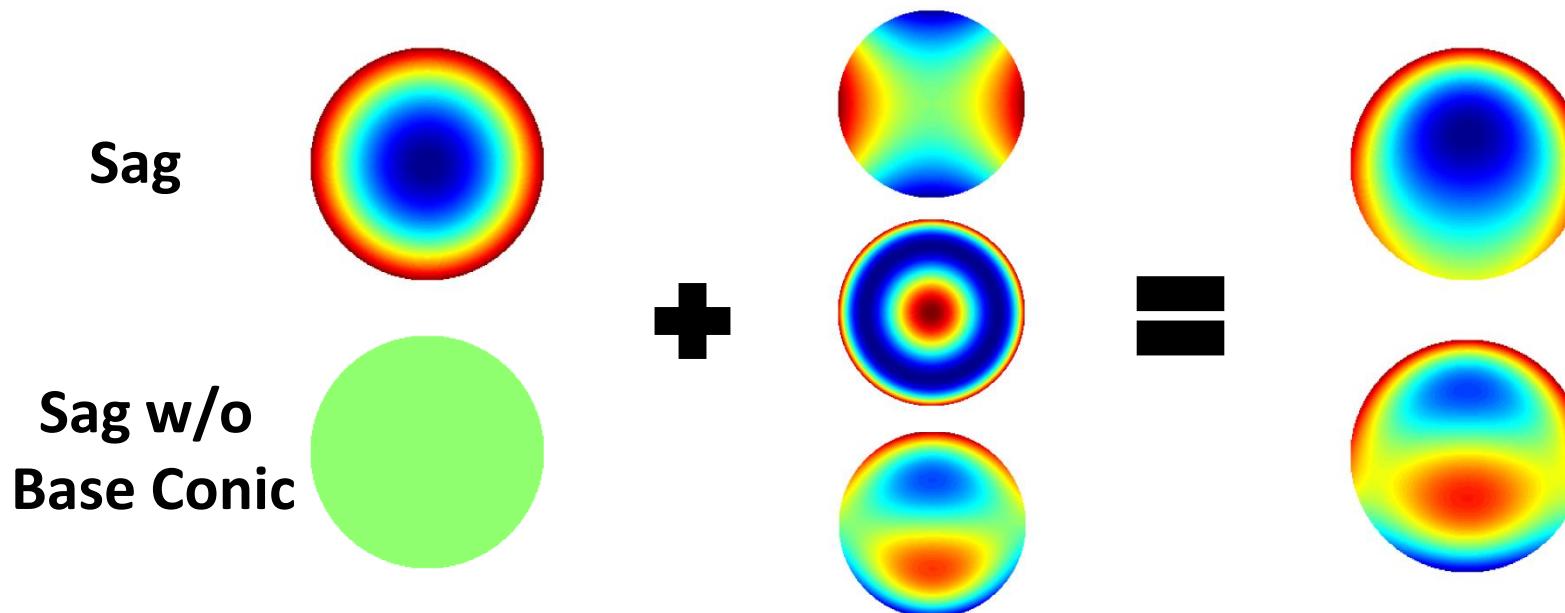
φ -Polynomial Surface Type

- A surface whose departure from a sphere
 - Varies with radial distance from center
 - Varies with clocking angle
 - Frequency of N cycles per roundtrip in the aperture
- Sag of optical surface is no longer limited to be rotationally symmetric
- Additional degree(s) of freedom
 - Surface can correct for asymmetric aberrations (i.e. coma) within an optical design

Zernike Polynomial Surface

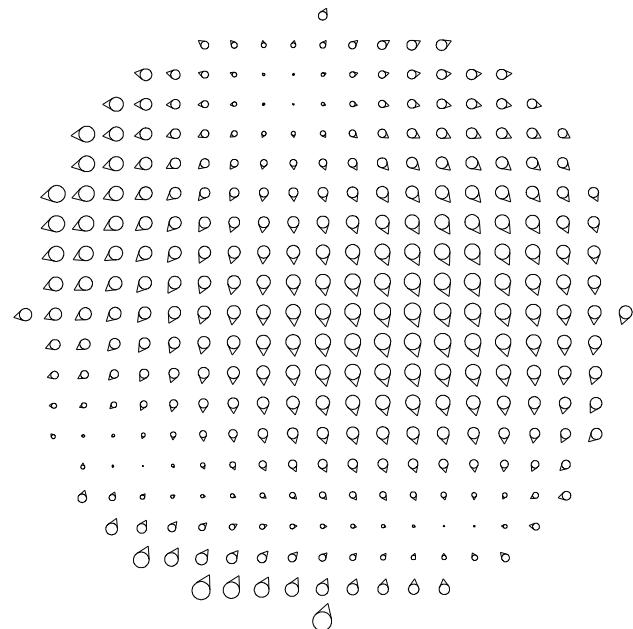
- Conic surface with FRINGE Zernike overlay

$$z = \frac{c\rho^2}{1 + \sqrt{1 - (1+k)c^2\rho^2}} + \sum_{j=1}^{37} C_j Z_j$$



Optical Design Tools

- Nodal Aberration Theory (NAT)
 - Foundation for behavior of **ANY** optical imaging system with a circular or near circular (within ~30%) pupil
 - There are **NO** new aberrations
 - Aberrations have a new dependence in field
 - Nodes are zeros of aberration
- Full Field Display
 - Computes Zernike coefficients
 - Throughout FOV over grid of points
 - Displays coefficients
 - Magnitude/Orientation

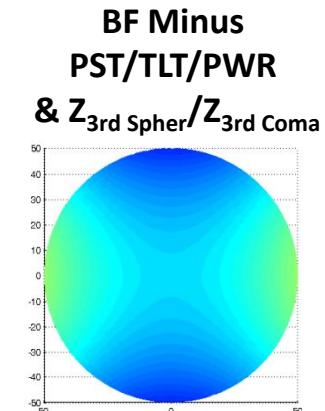
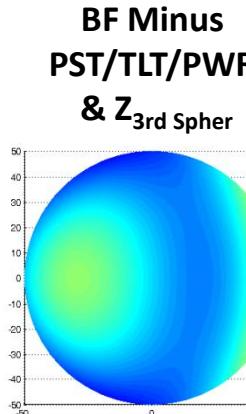
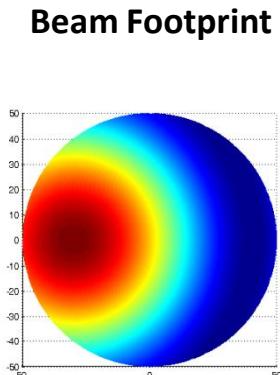
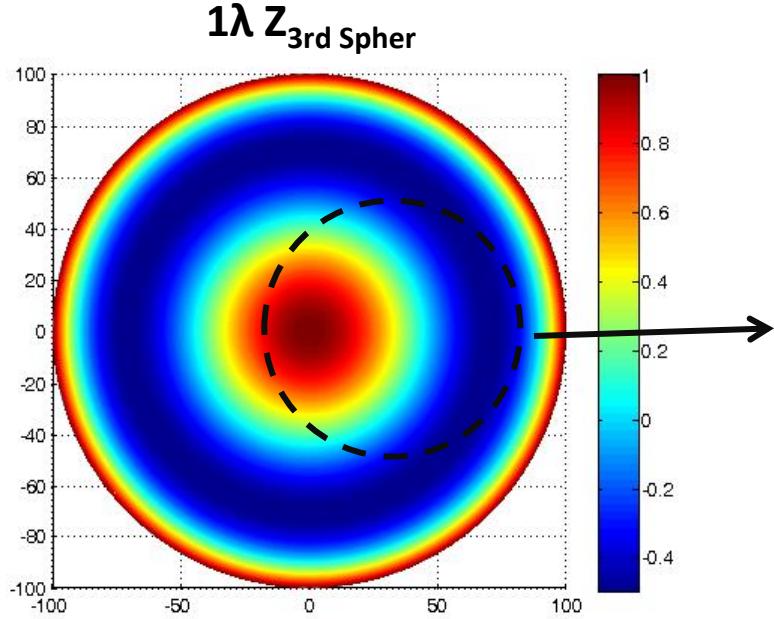


Non-Symmetric Surfaces in NAT

- Two places for non-symmetric surfaces to lie
 - At the stop surface
 - Beam footprint for all fields fills stop
 - All fields are influenced by non-symmetric surface equally
 - Result is **field-constant contribution** to aberration function
 - Away from the stop surface
 - Beam footprint is different for each field
 - Each field is influenced differently by non-symmetric surface
 - Result is both **field-constant and field-dependent contributions** to aberration function

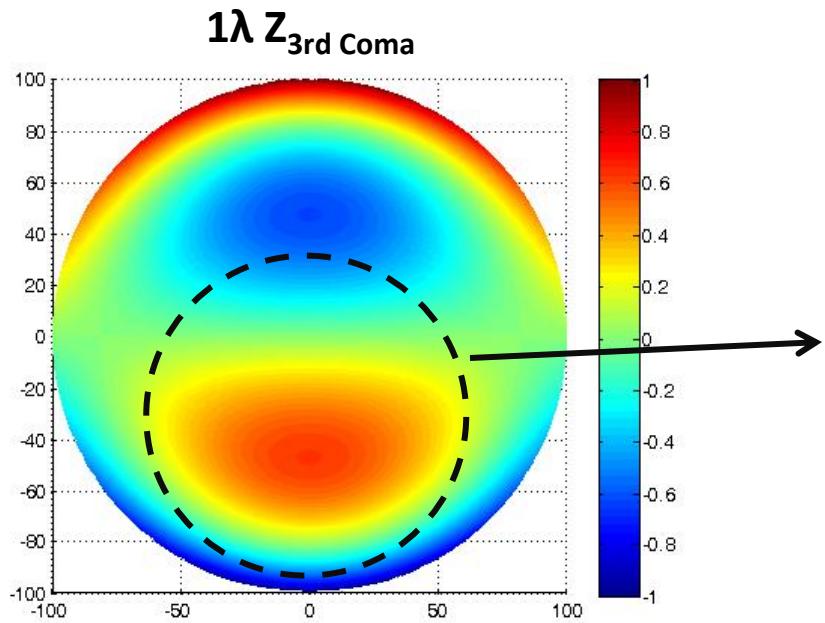
Example: Zernike 3rd Ord. Spherical

- Beam Footprint incident on $Z_{3\text{rd Spher}}$ surface
 - Generates $Z_{3\text{rd Spher}}$, $Z_{3\text{rd Coma}}$, $Z_{3\text{rd Astig}}$ and low order

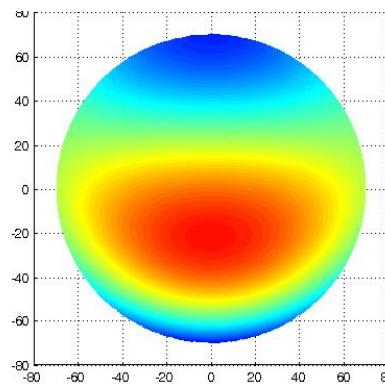


Example: Zernike 3rd Ord. Coma

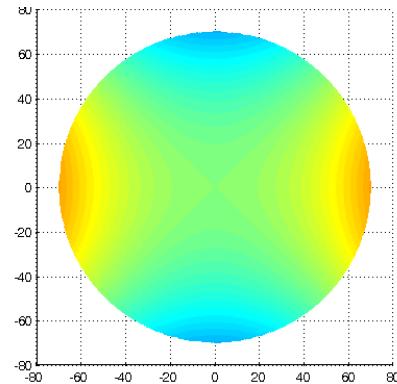
- Beam Footprint incident on $Z_{\text{3rd Coma}}$ surface
 - Generates $Z_{\text{3rd Coma}}$, $Z_{\text{3rd Astig}}$ and low order



Beam Footprint

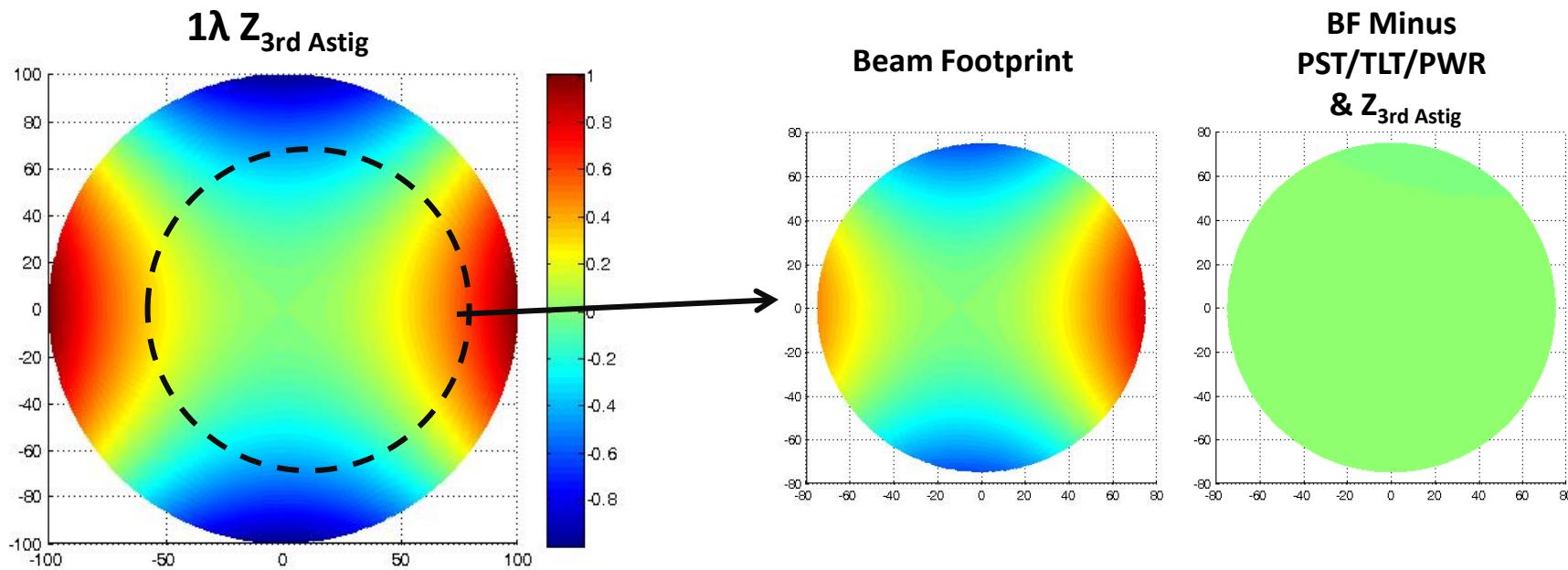


BF Minus
PST/TLT/PWR
& $Z_{\text{3rd Coma}}$



Example: Zernike 3rd Ord. Astigmatism

- Beam Footprint incident on $Z_{3\text{rd Astig}}$ surface
 - Generates $Z_{3\text{rd Astig}}$ and low order

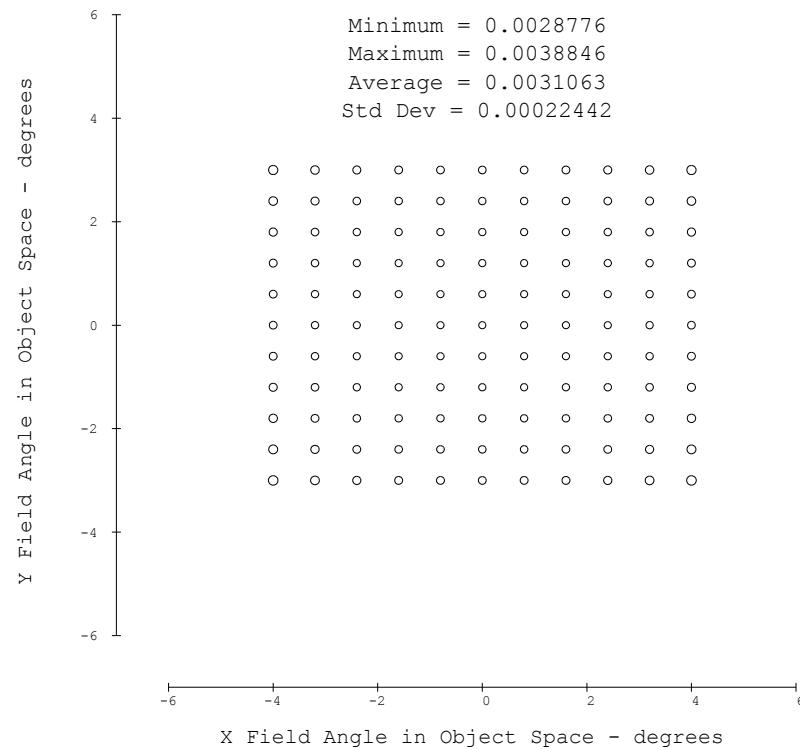
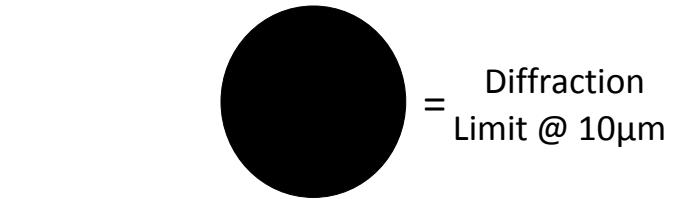
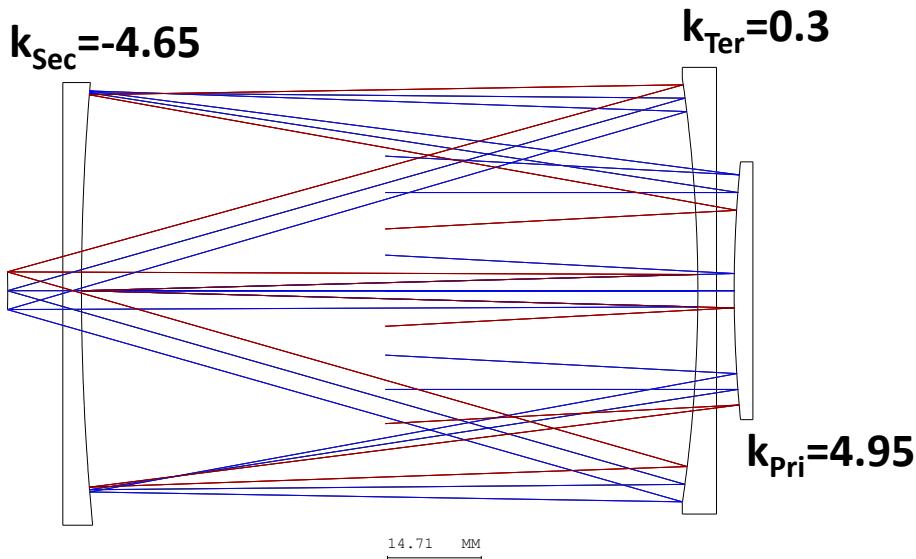


Design Example

- F/1.9, 10° FFOV Low Cost LWIR Imager
 - Micro-Bolometer
 - 320x240 pixel resolution, 25 μ m pitch
 - Uncooled
 - Does not need accessible exit pupil
 - Requires fast system F/#
 - Drives up spherical volume of system
 - Compact Geometry
 - Large input port in small spherical volume
 - Unobscured

Potential On-Axis Solution

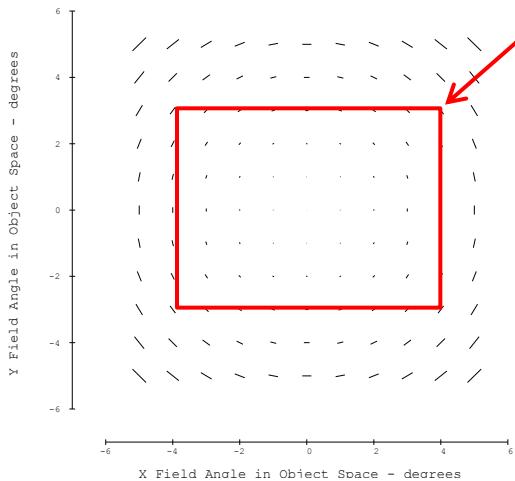
- NPP Solution
 - RMS wavefront error less than $<\lambda/250$ over 10° FFOV
 - 100% Obscured



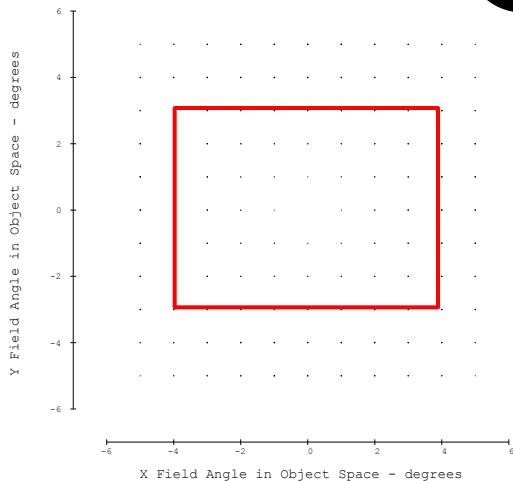
Aberration Contributions

$Z_{\text{3rd Astig}}$

10° diagonal FFOV

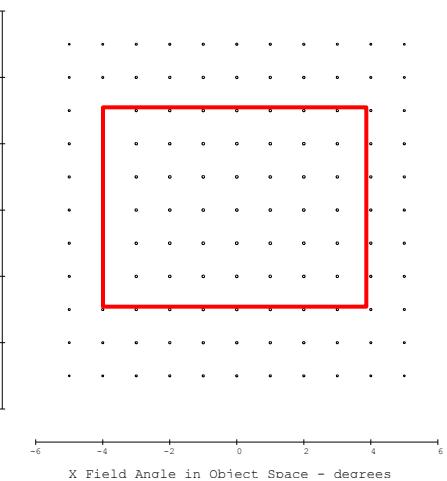


$Z_{\text{3rd Coma}}$

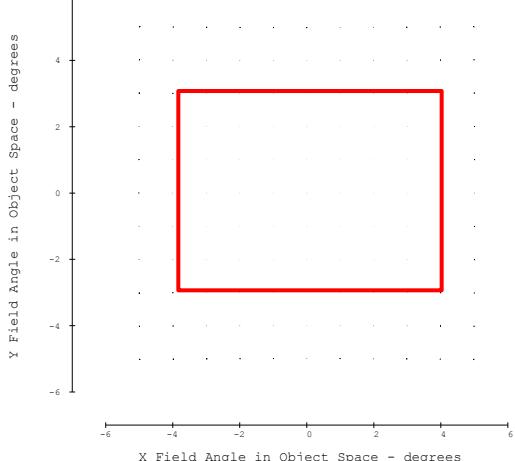


= Diffraction
Limit @ 10μm

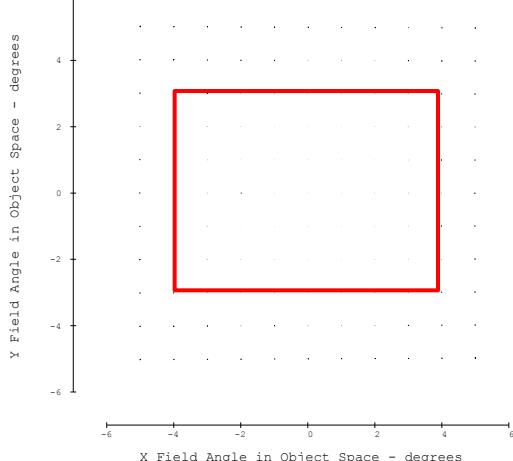
$Z_{\text{3rd Spher}}$



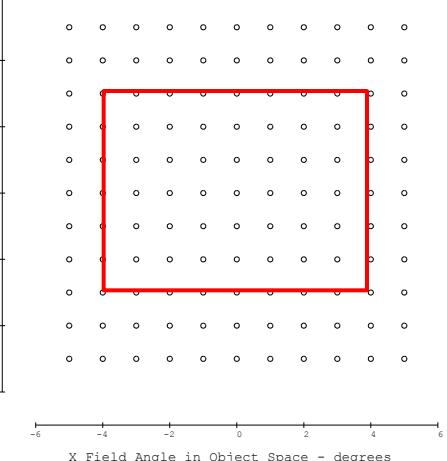
$Z_{\text{Ellip. Coma}}$



$Z_{\text{Obl. Spher.}}$

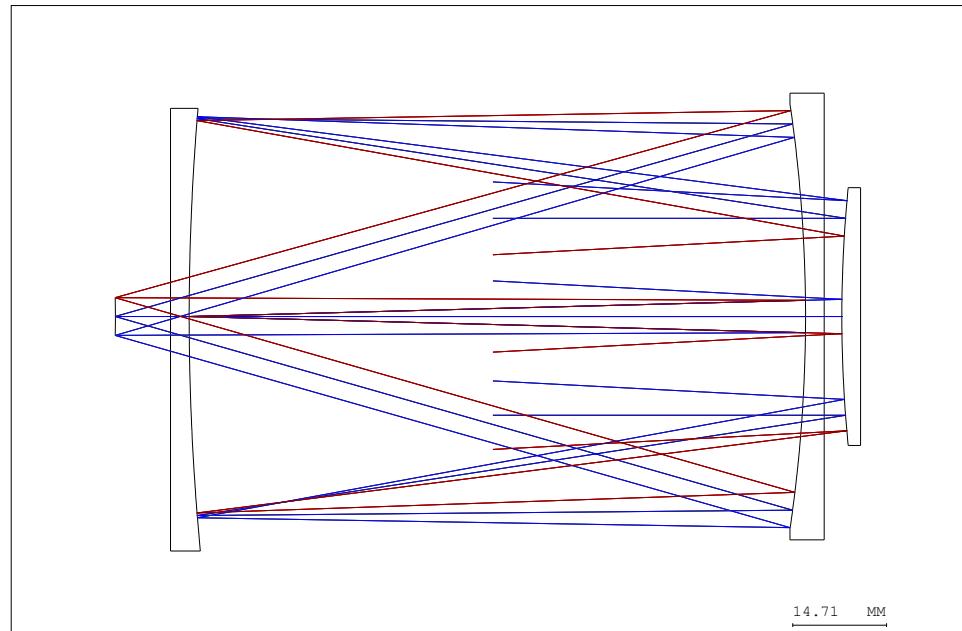


$Z_{\text{5th Spher}}$



Creating an Unobscured System

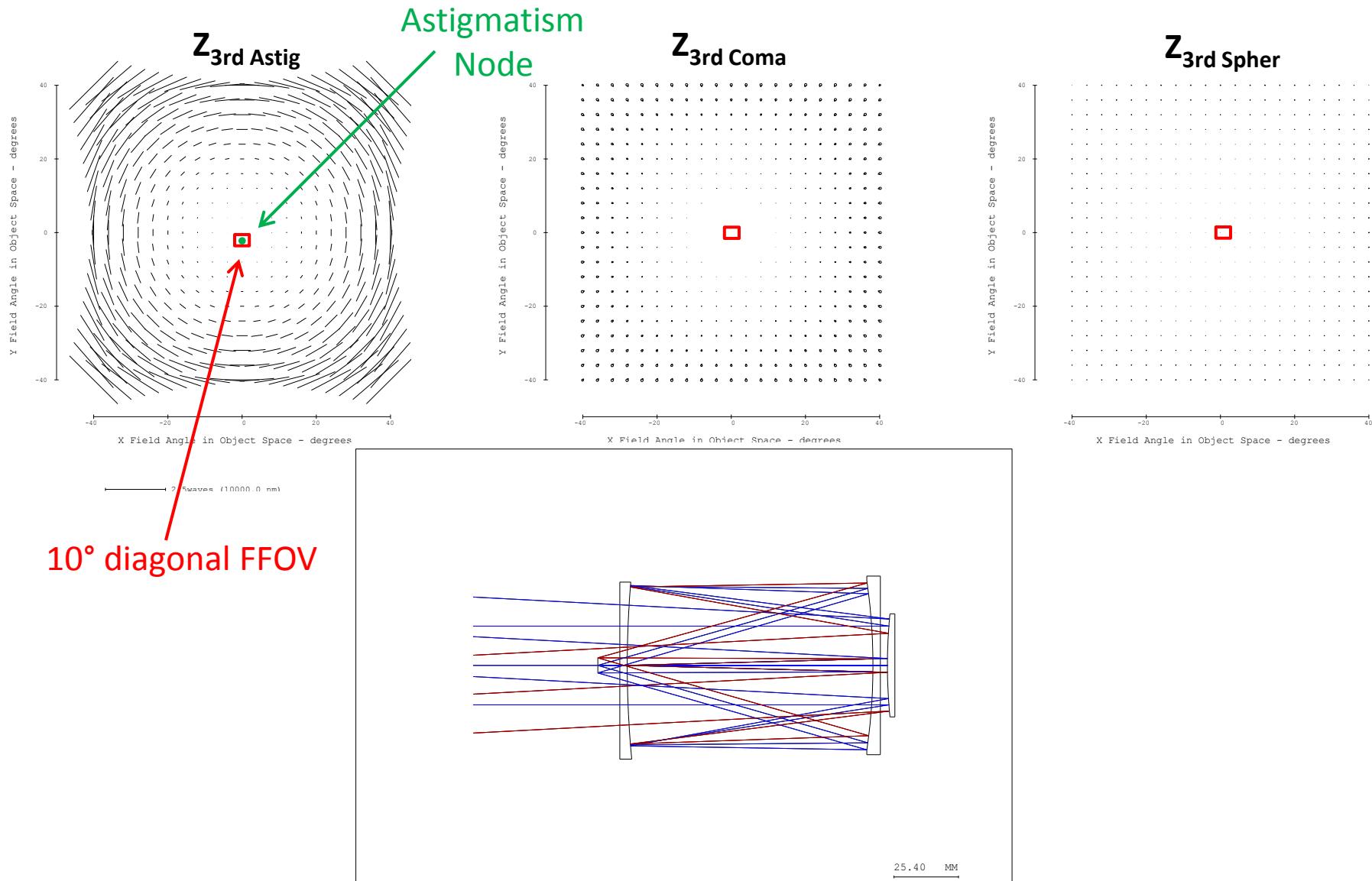
- Off-axis in aperture?
 - Shape of primary prohibitive
- Off-axis in field?
 - Need to use large field angles
- Tilt the surfaces?



Tilting the Surfaces?

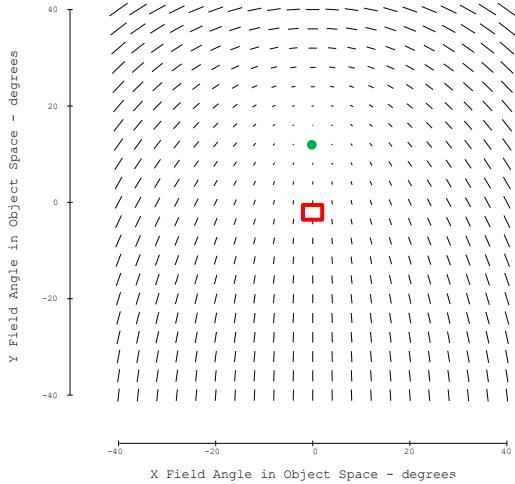
- To date, most solutions have been offset in aperture and/or field
- Invoking ϕ -polynomial surfaces has created for truly off-axis designs with high performance

Tilt the Surfaces (On-Axis)

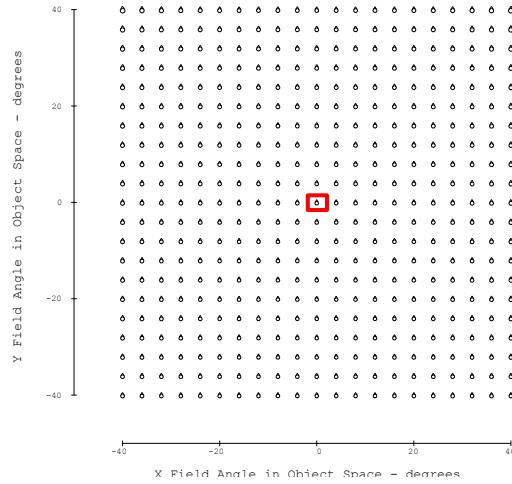


Tilt the Surfaces (25% Tilt)

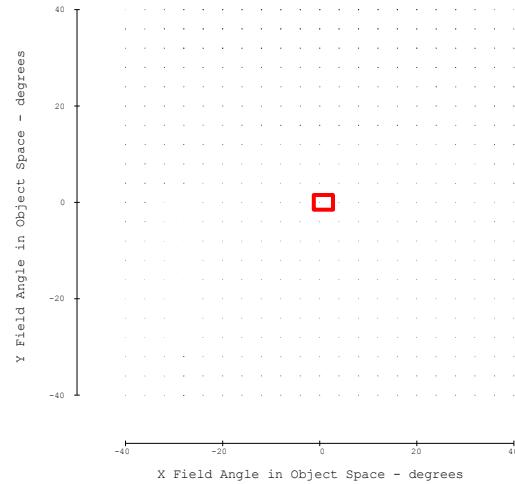
Z_{3rd} Astig



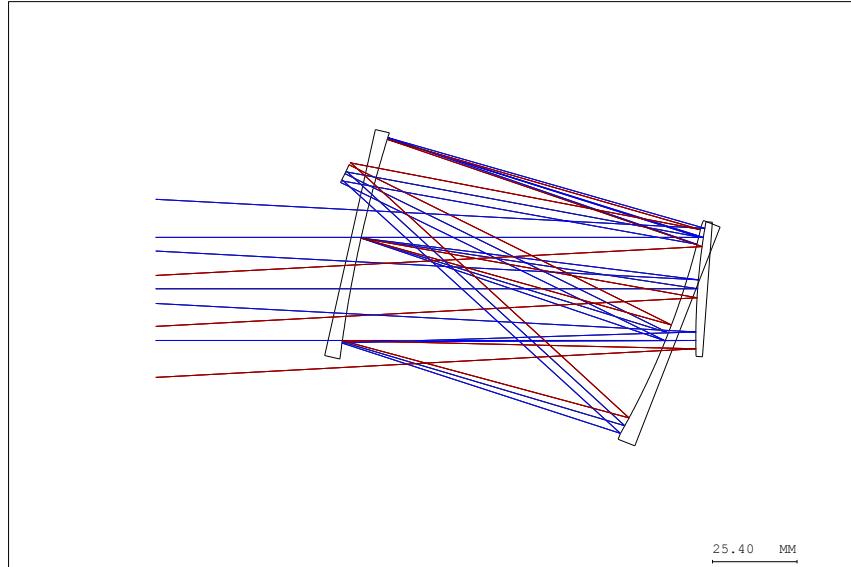
Z_{3rd} Coma



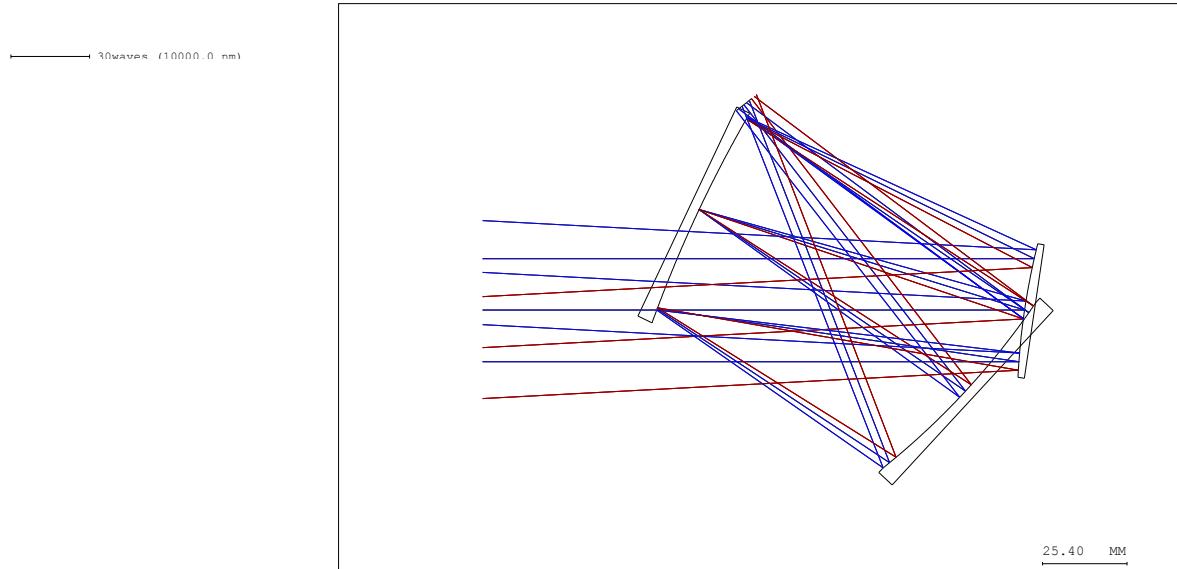
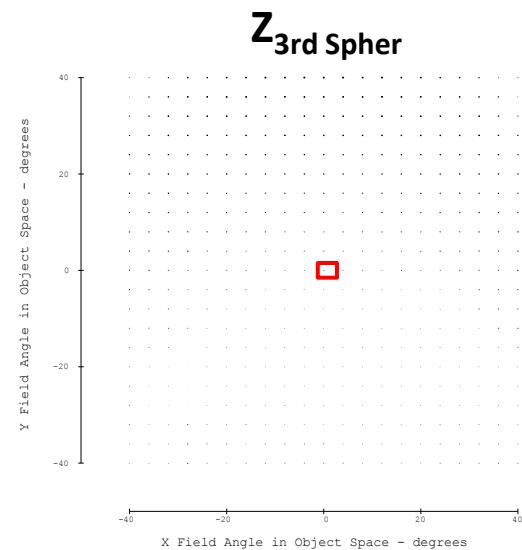
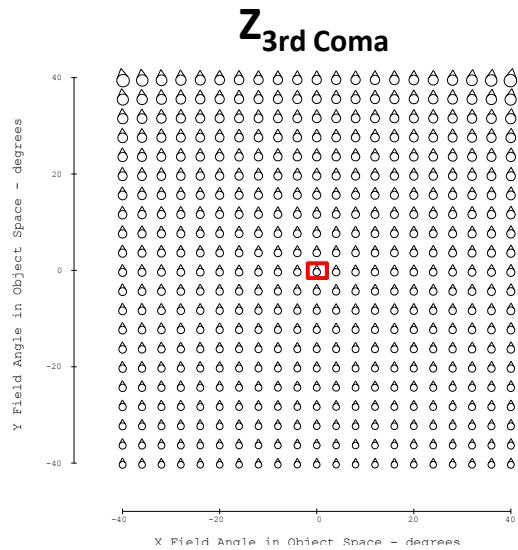
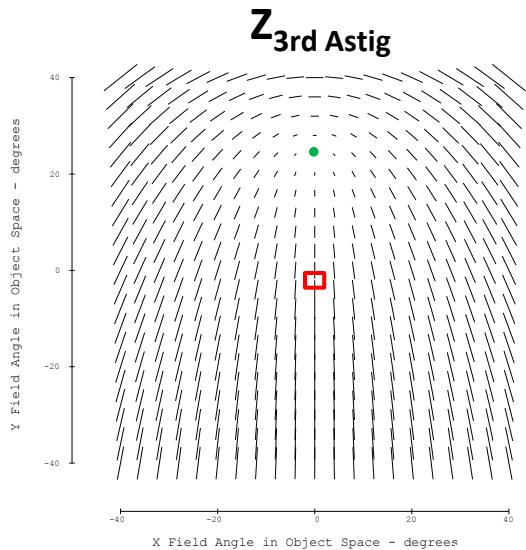
Z_{3rd} Spher



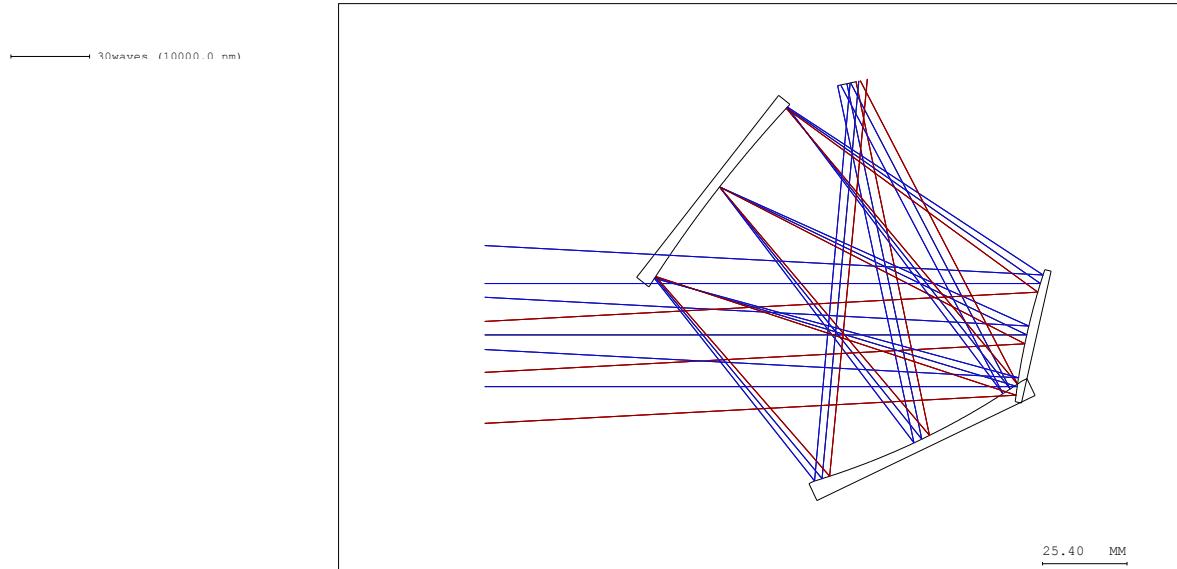
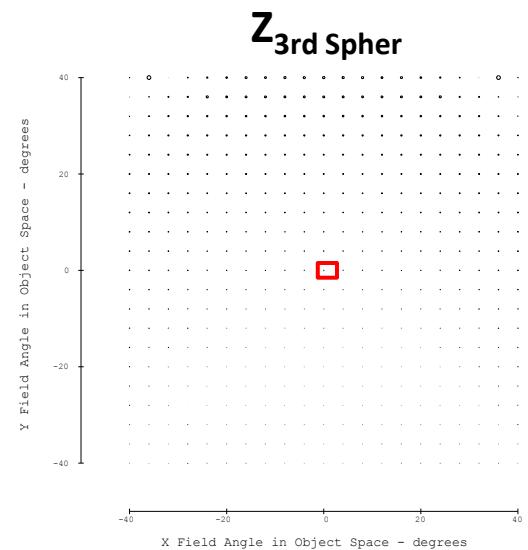
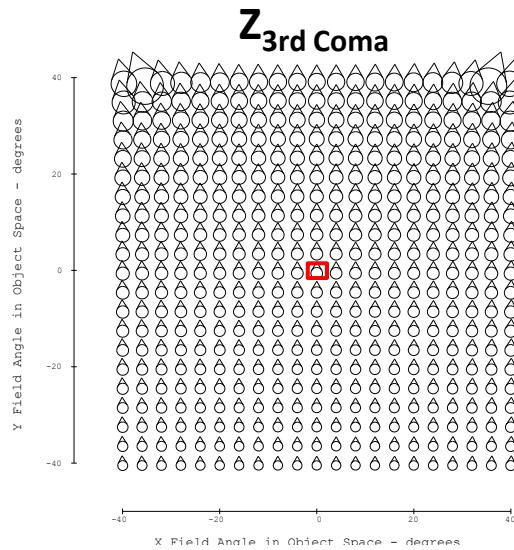
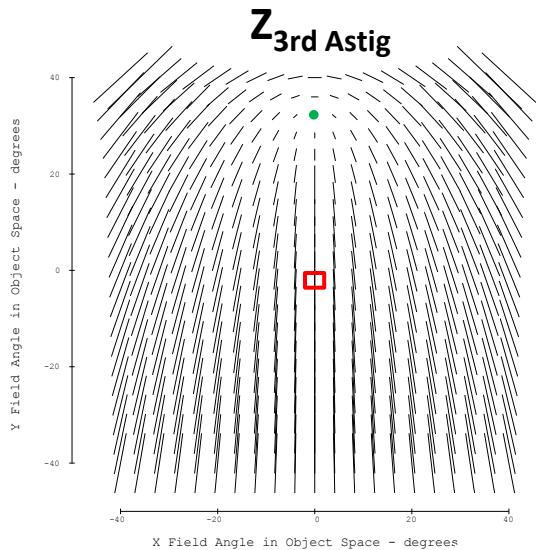
30waves (10000.0 nm)



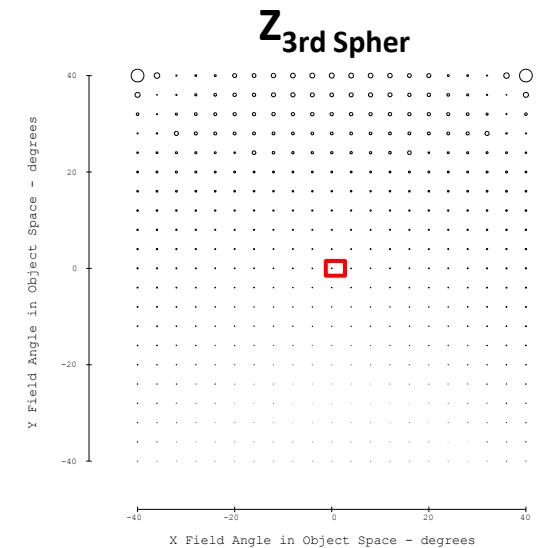
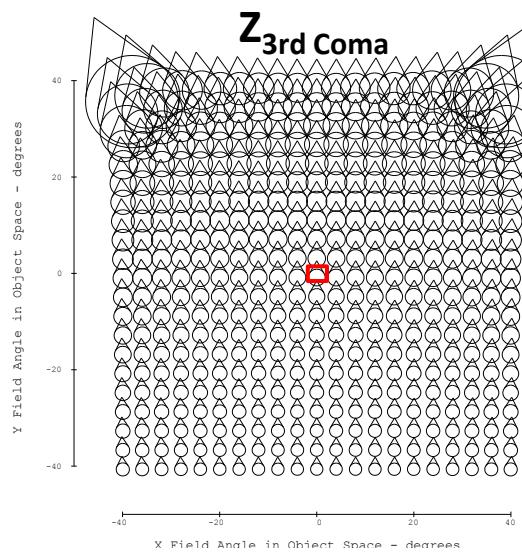
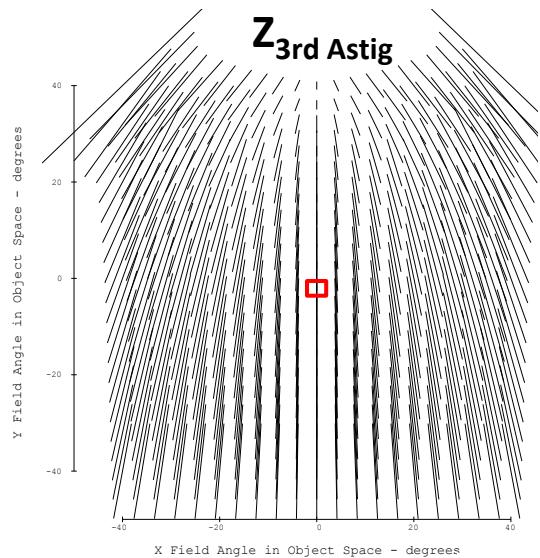
Tilt the Surfaces (50% Tilt)



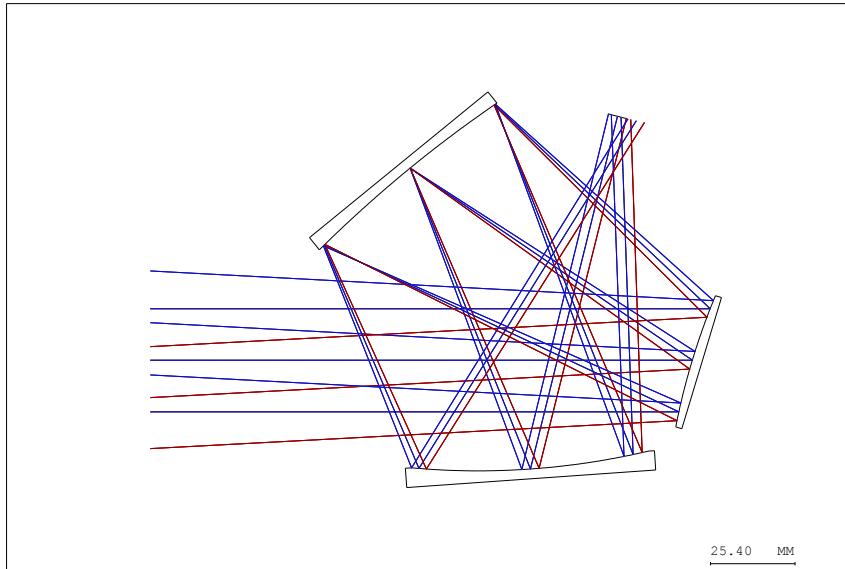
Tilt the Surfaces (75% Tilt)



Tilt the Surfaces (100% Tilt)



30waves (10000.0 nm)



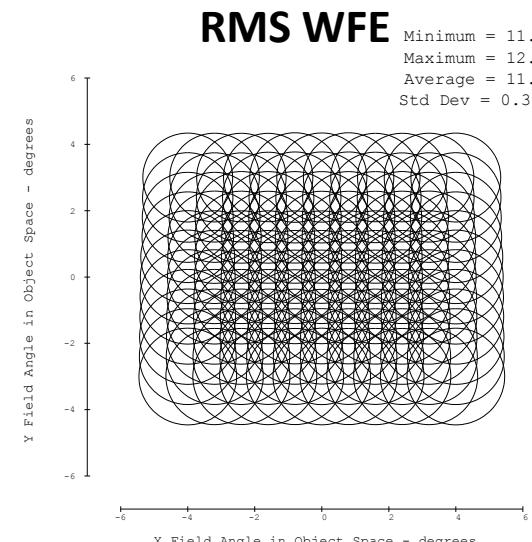
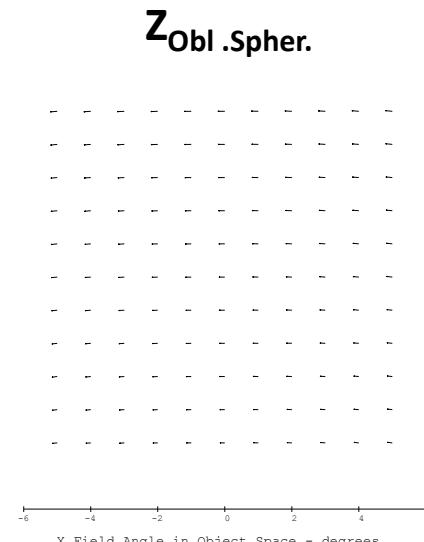
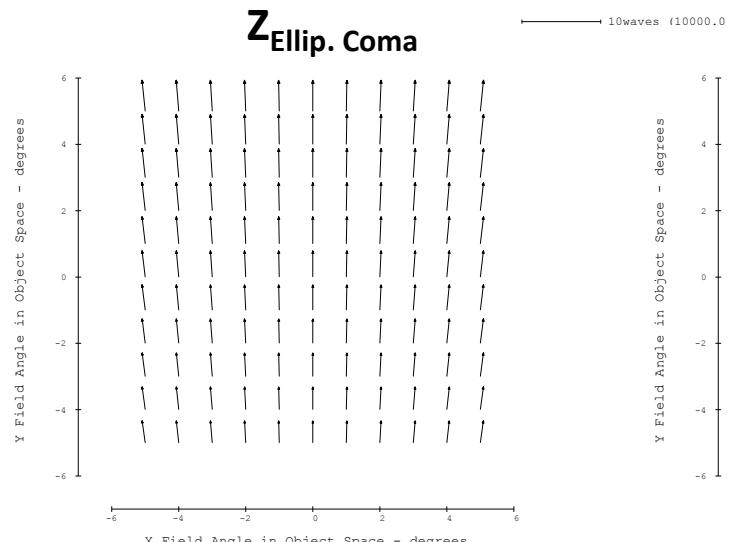
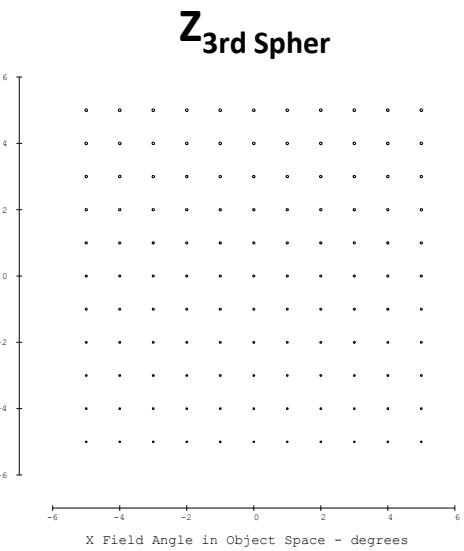
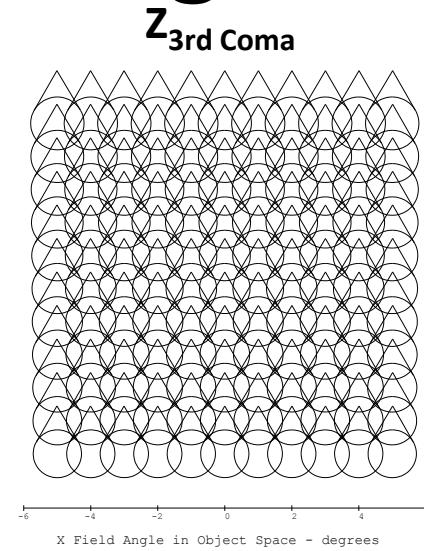
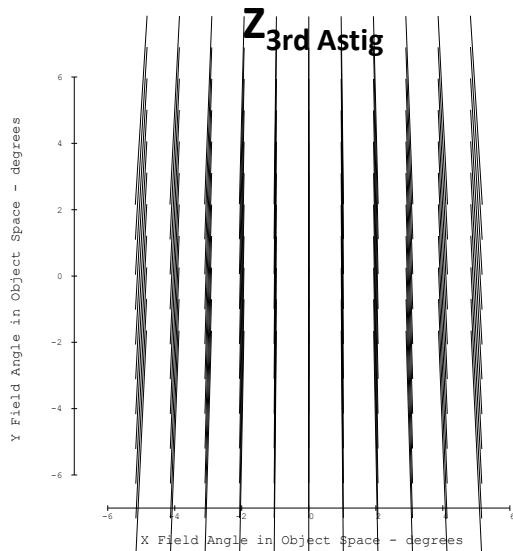
Recovering the Performance

- With tilted mirrors for unobscured system
 - Nearly constant “field” aberrations within 10° FFOV
 - True for low & high order terms
 - Negligible effect on spherical aberration

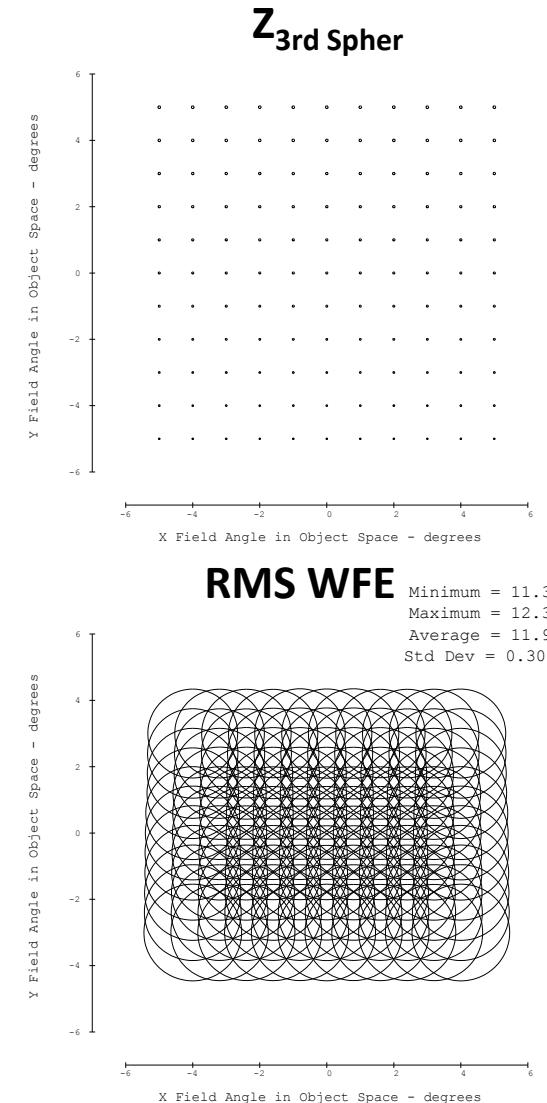
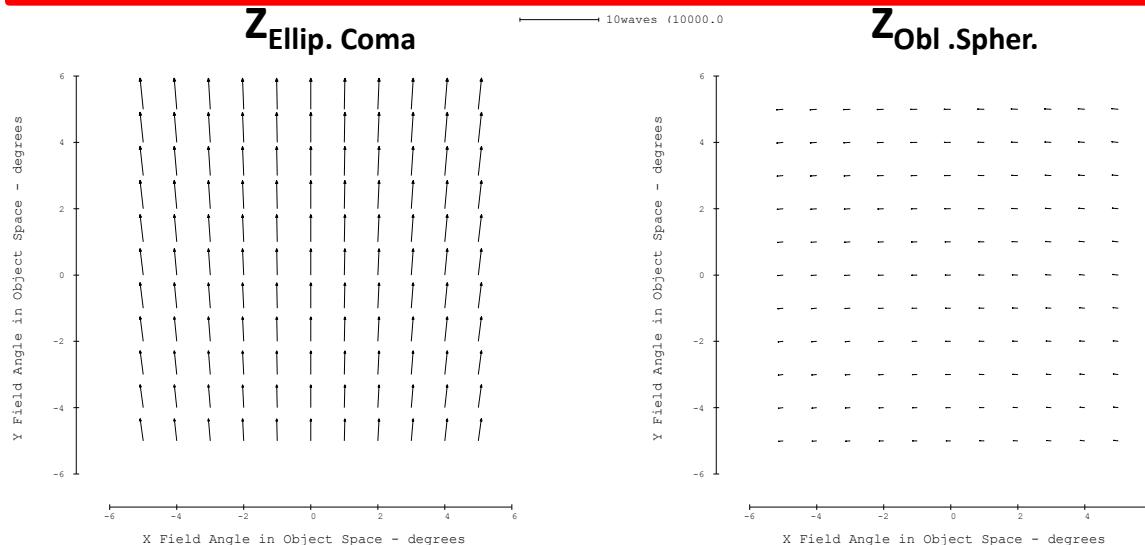
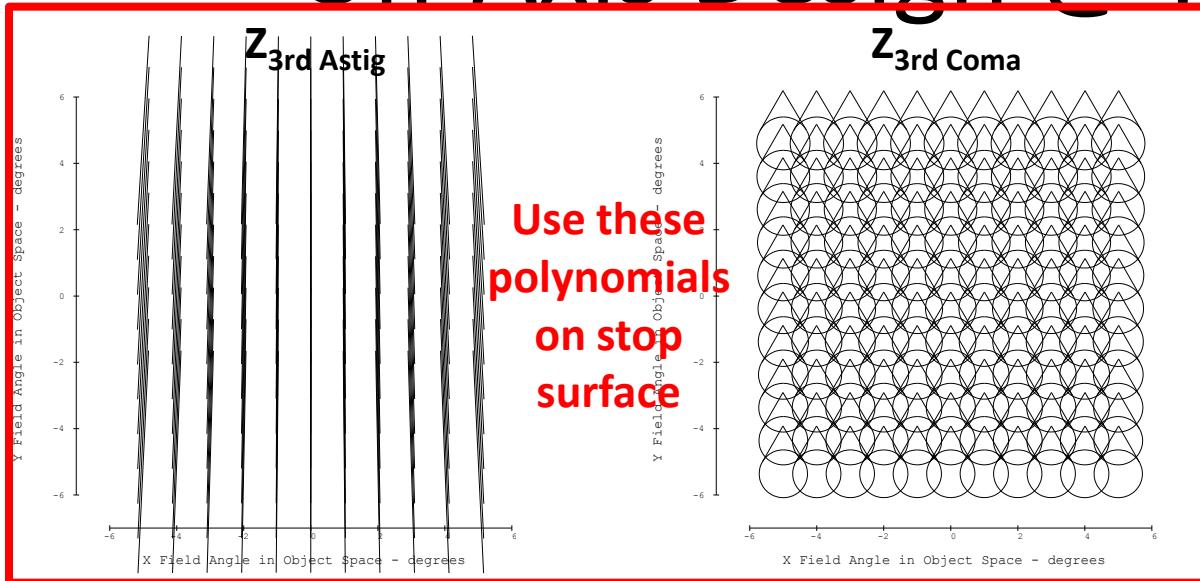
Design Strategy I

- Use ϕ -polynomials at stop surface to remove field-constant contributions to the aberration function

On-Axis Design @ Full Tilt

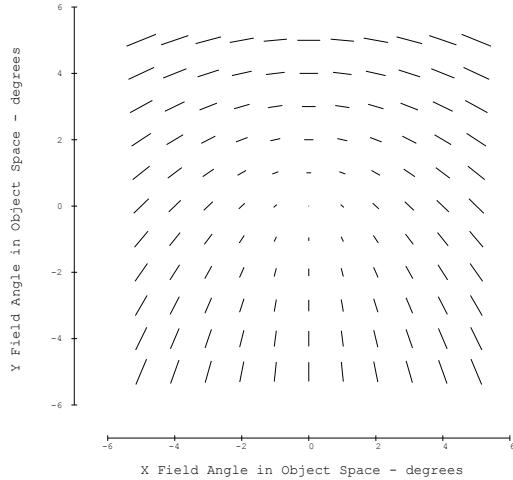


On-Axis Design @ Full Tilt

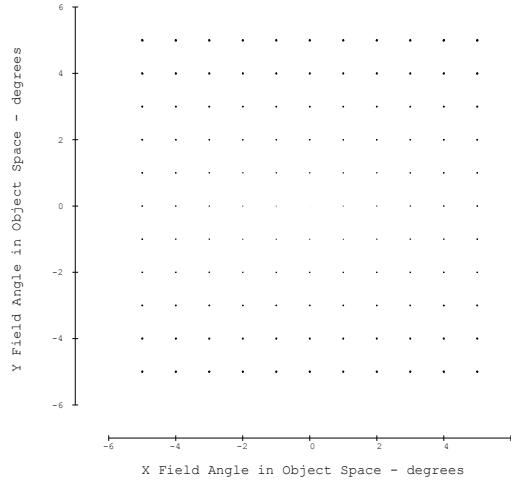


Optimized Design with Strategy I

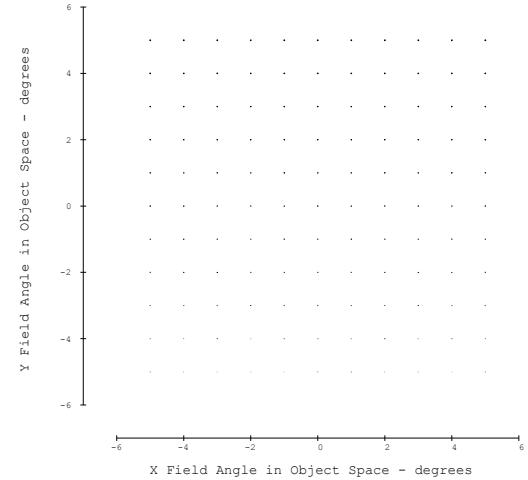
$Z_{\text{3rd Astig}}$



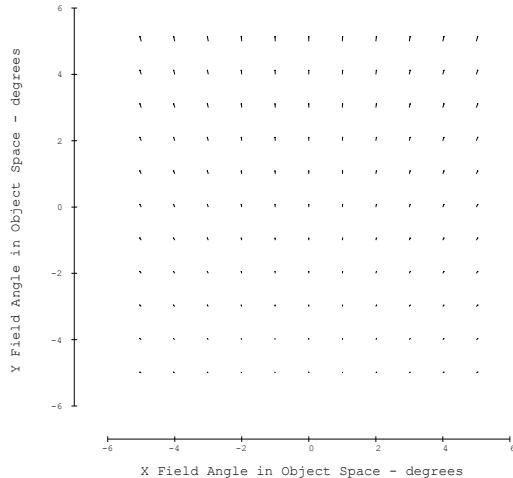
$Z_{\text{3rd Coma}}$



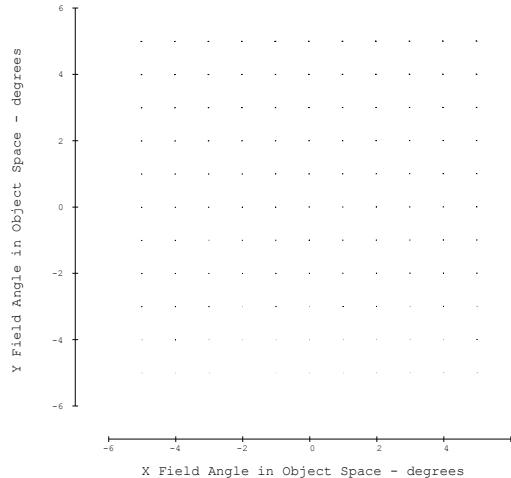
$Z_{\text{3rd Spher}}$



$Z_{\text{Ellip. Coma}}$

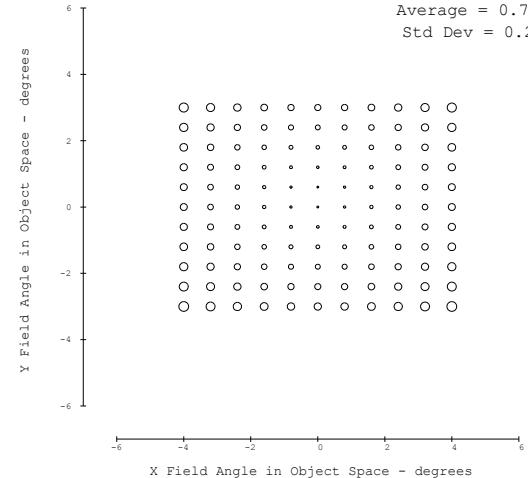


$Z_{\text{Obl.Spher.}}$



RMS WFE

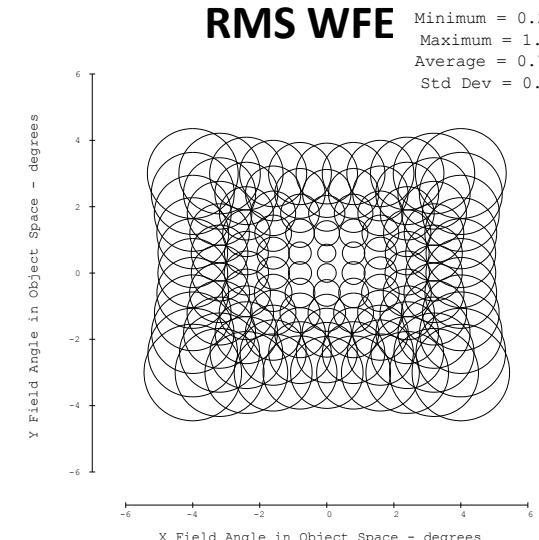
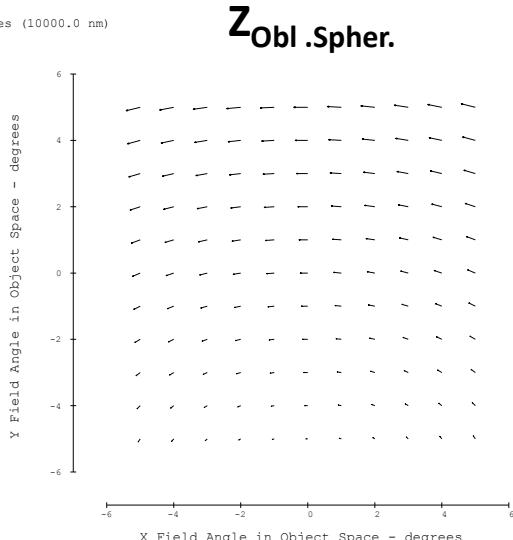
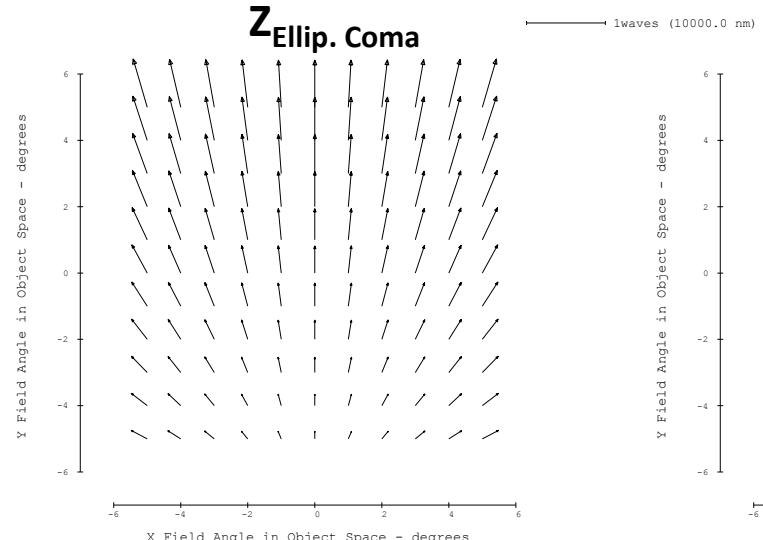
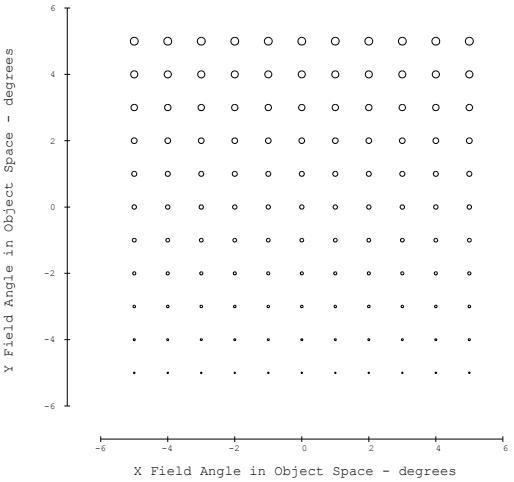
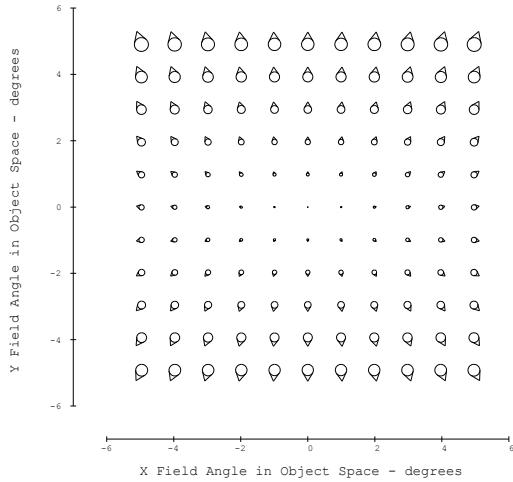
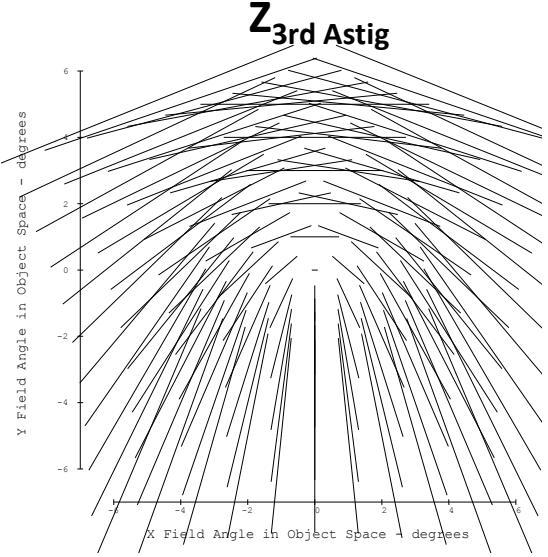
Minimum = 0.22968
Maximum = 1.2374
Average = 0.74312
Std Dev = 0.2417



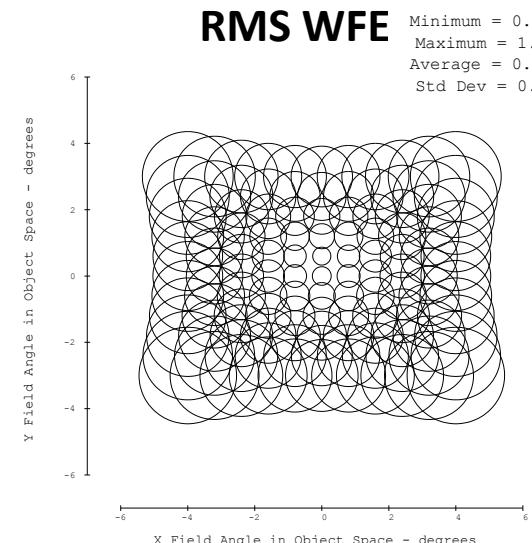
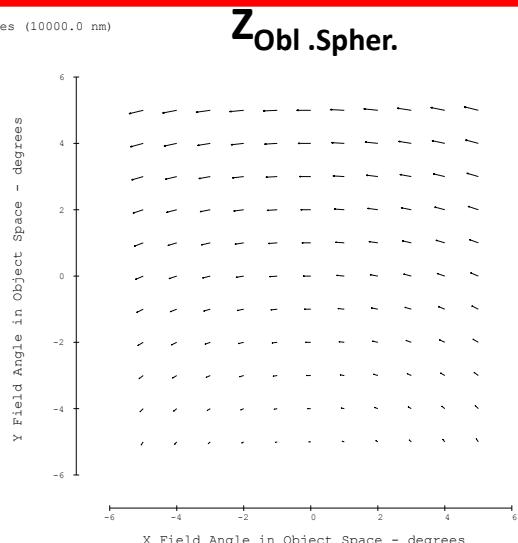
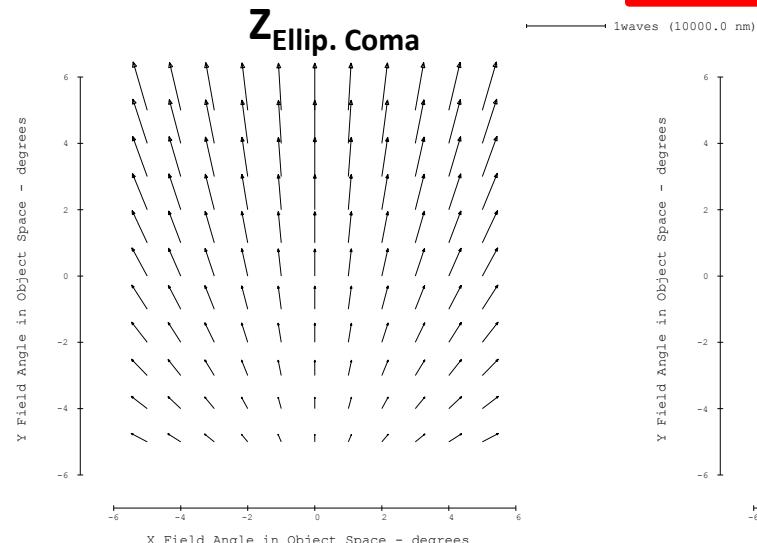
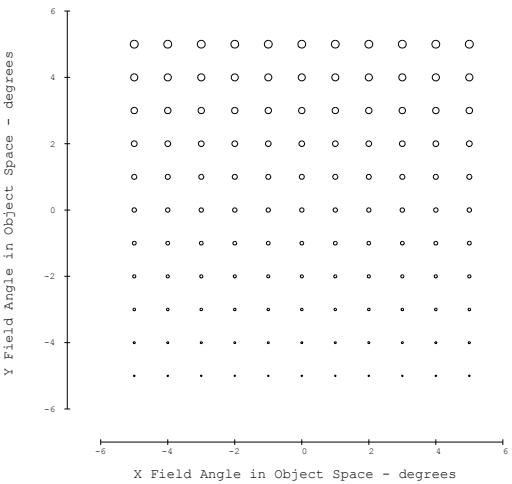
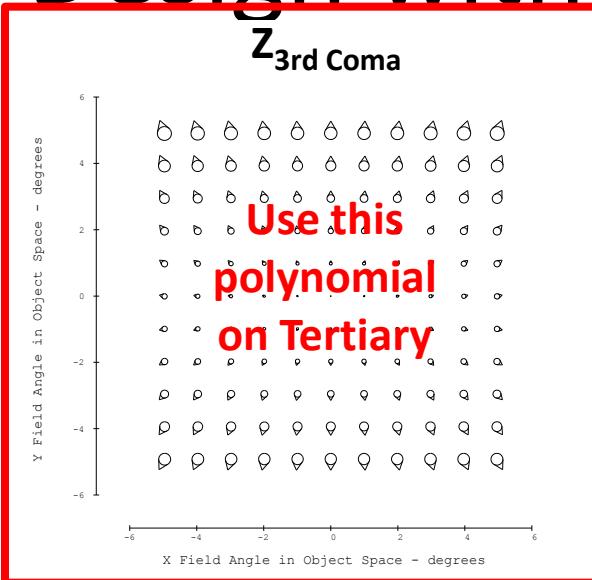
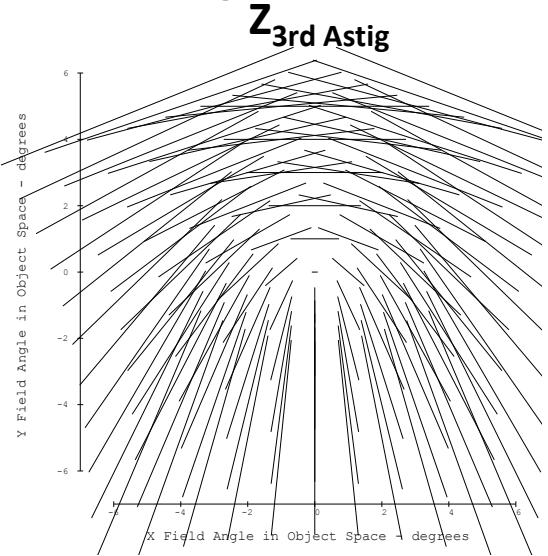
Design Strategy II

- Use ϕ -polynomials away from stop surface to counteract field dependent aberrations

Optimized Design with Strategy I

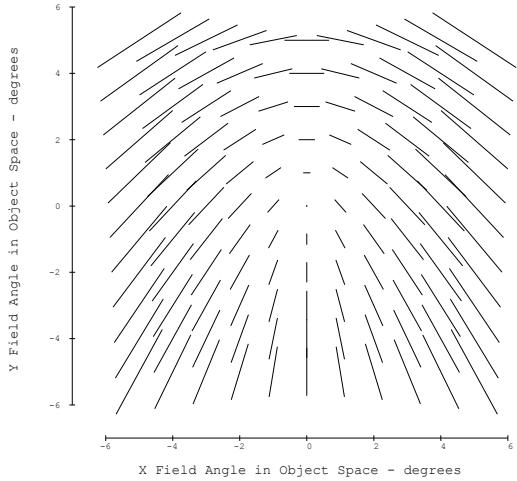


Optimized Design with Strategy I

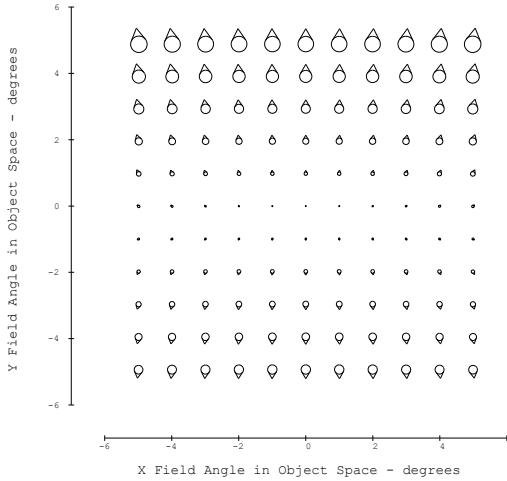


Optimized Design with Strategy II

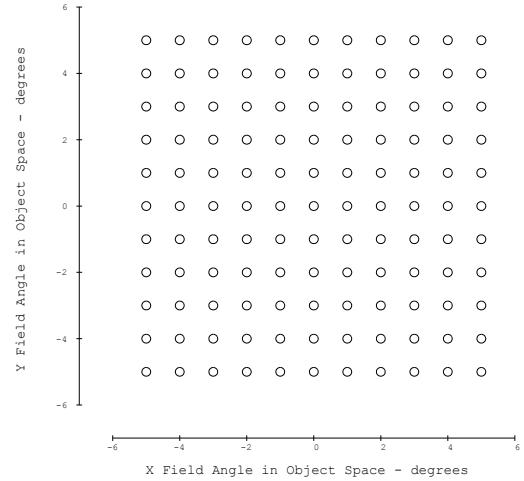
$Z_{\text{3rd Astig}}$



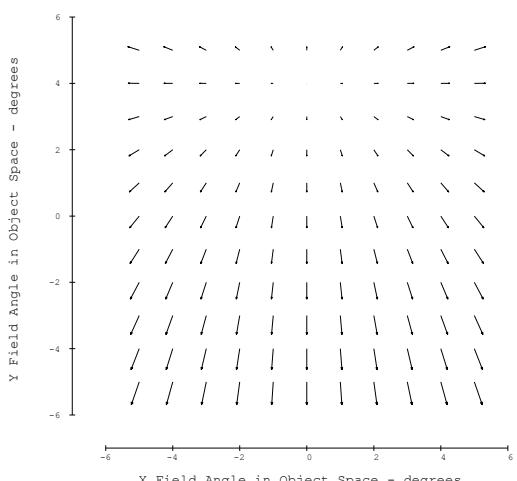
$Z_{\text{3rd Coma}}$



$Z_{\text{3rd Spher}}$

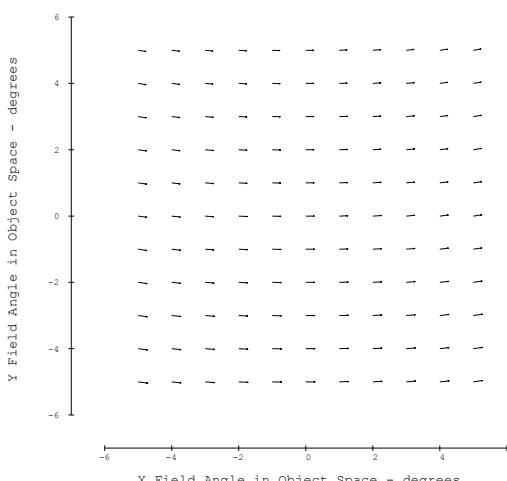


$Z_{\text{Ellip. Coma}}$



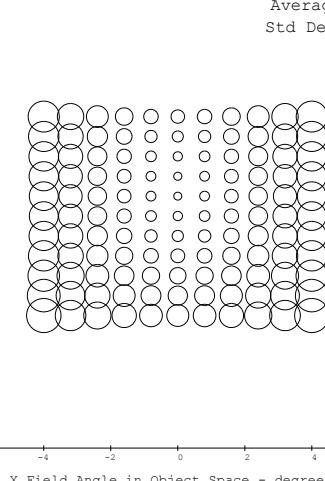
iwaves (10000.0 nm)

$Z_{\text{Obl.Spher.}}$



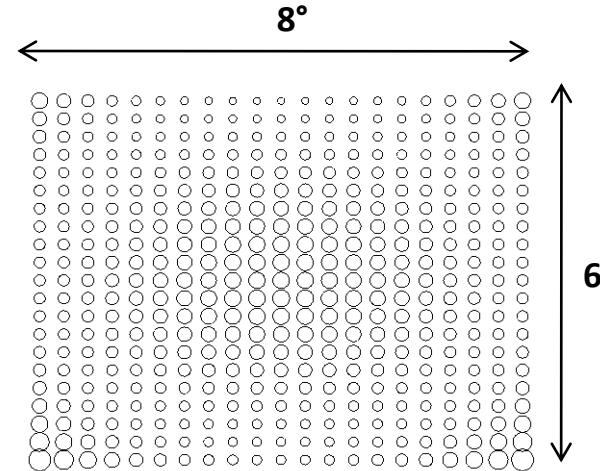
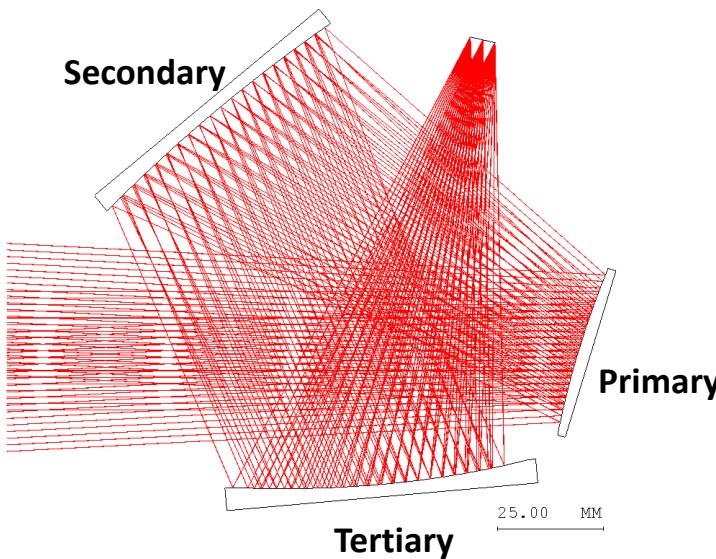
RMS WFE

Minimum = 0.10173
Maximum = 0.43653
Average = 0.26587
Std Dev = 0.088133



Final Optimized Solution

- With further implementation of design strategies I & II
 - Reach solution with RMS wavefront error at a $\lambda = 10 \mu\text{m}$ of less than $\lambda/50$ over 10° FFOV

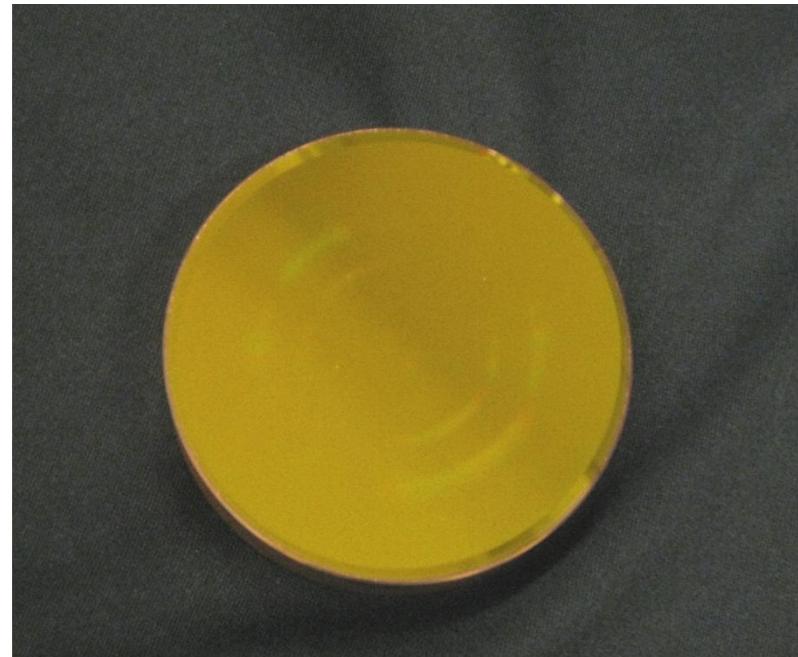
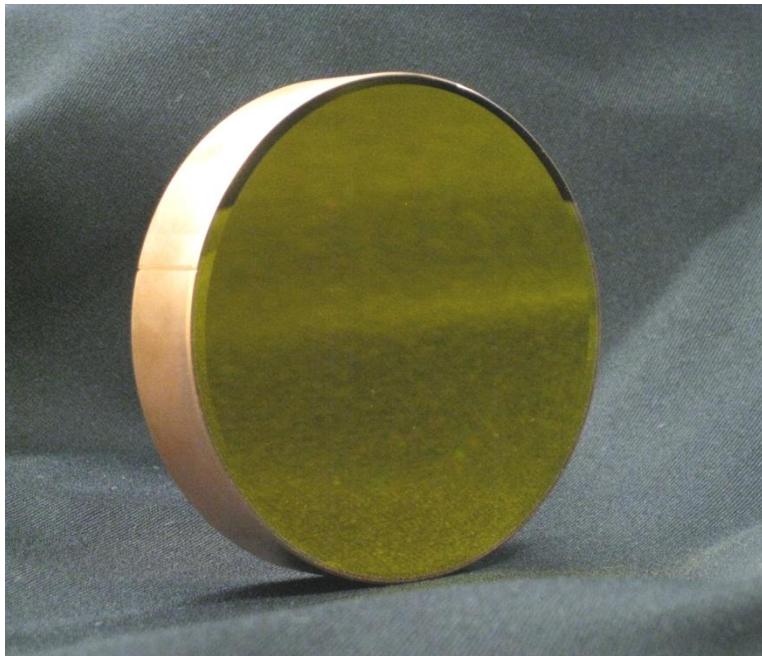


Minimum = 0.0049516
Maximum = 0.015382
Average = 0.0085467
Std Dev = 0.0017325

= Diffraction Limit @ 10μm

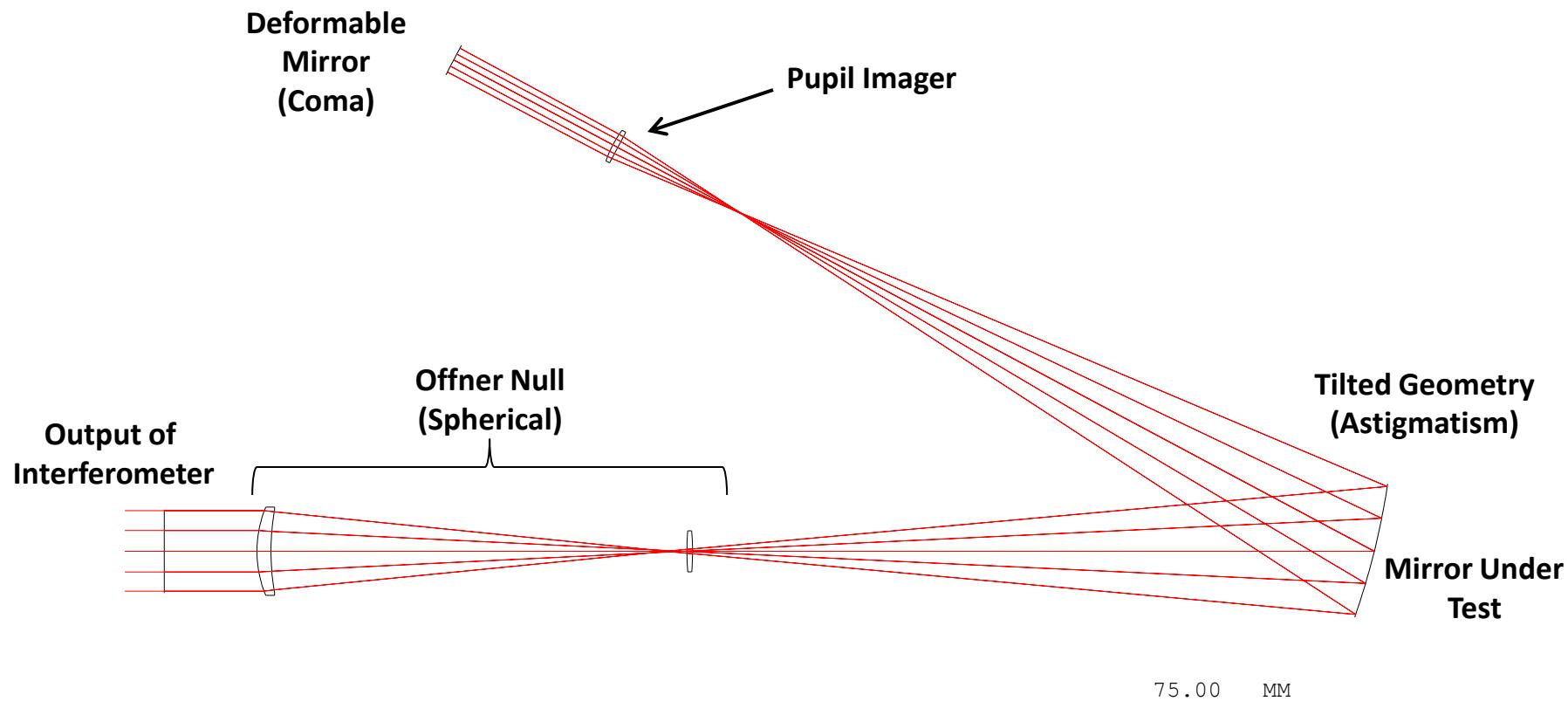
Fabrication

- Secondary mirror has been diamond turned by II-VI Infrared Inc.



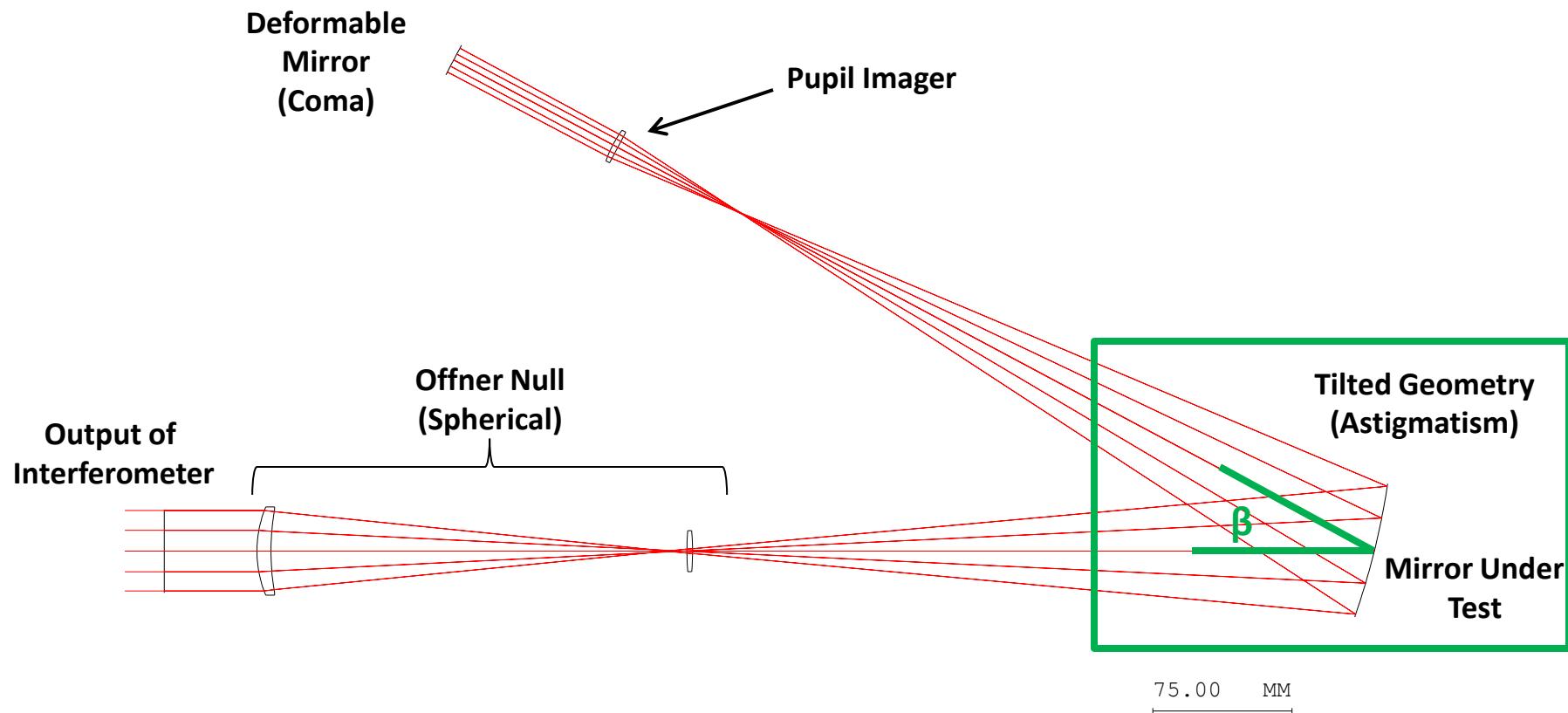
Metrology

- Acceptance testing/characterization configuration for the secondary mirror



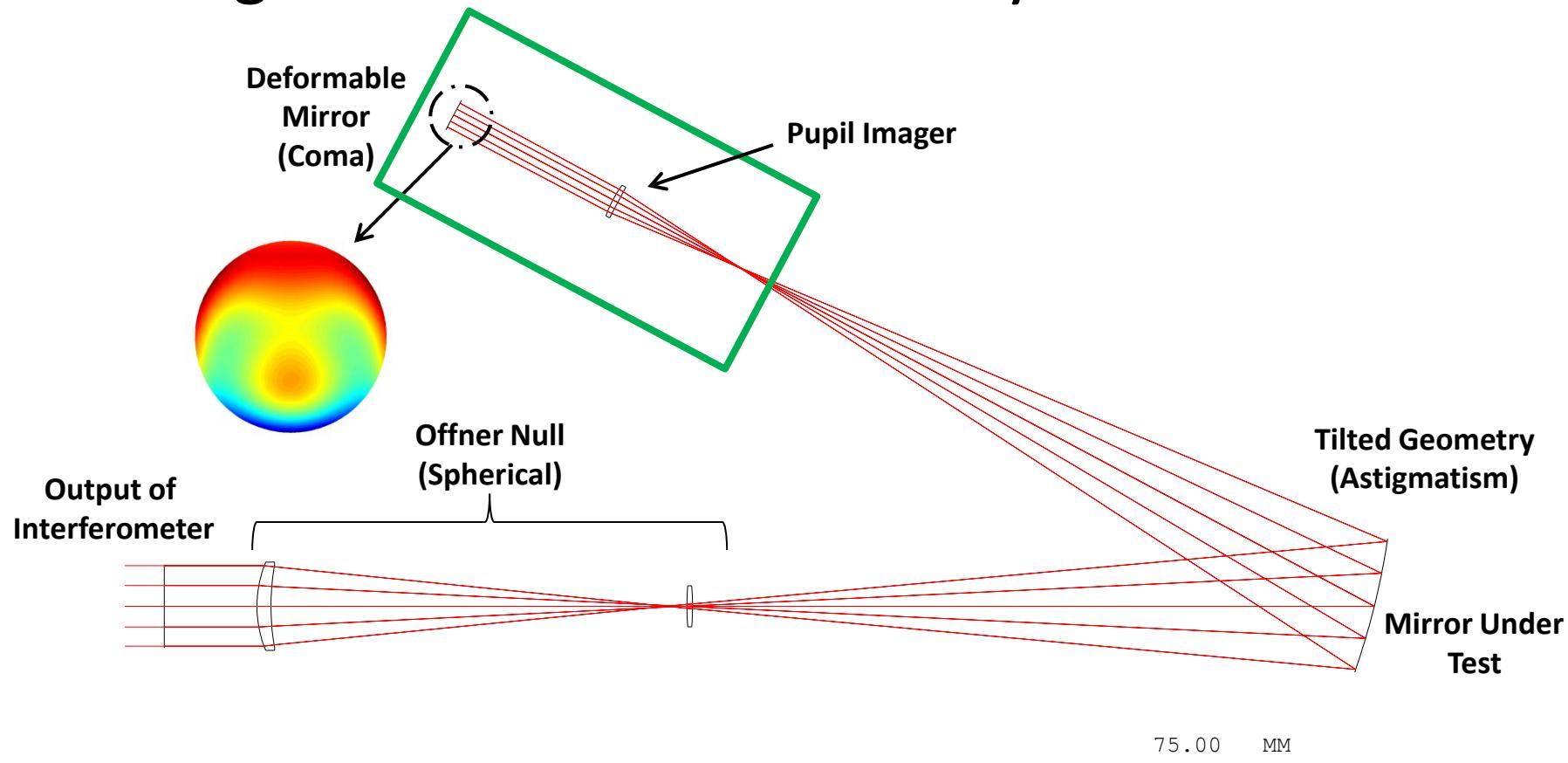
Metrology

- Acceptance testing/characterization configuration for the secondary mirror



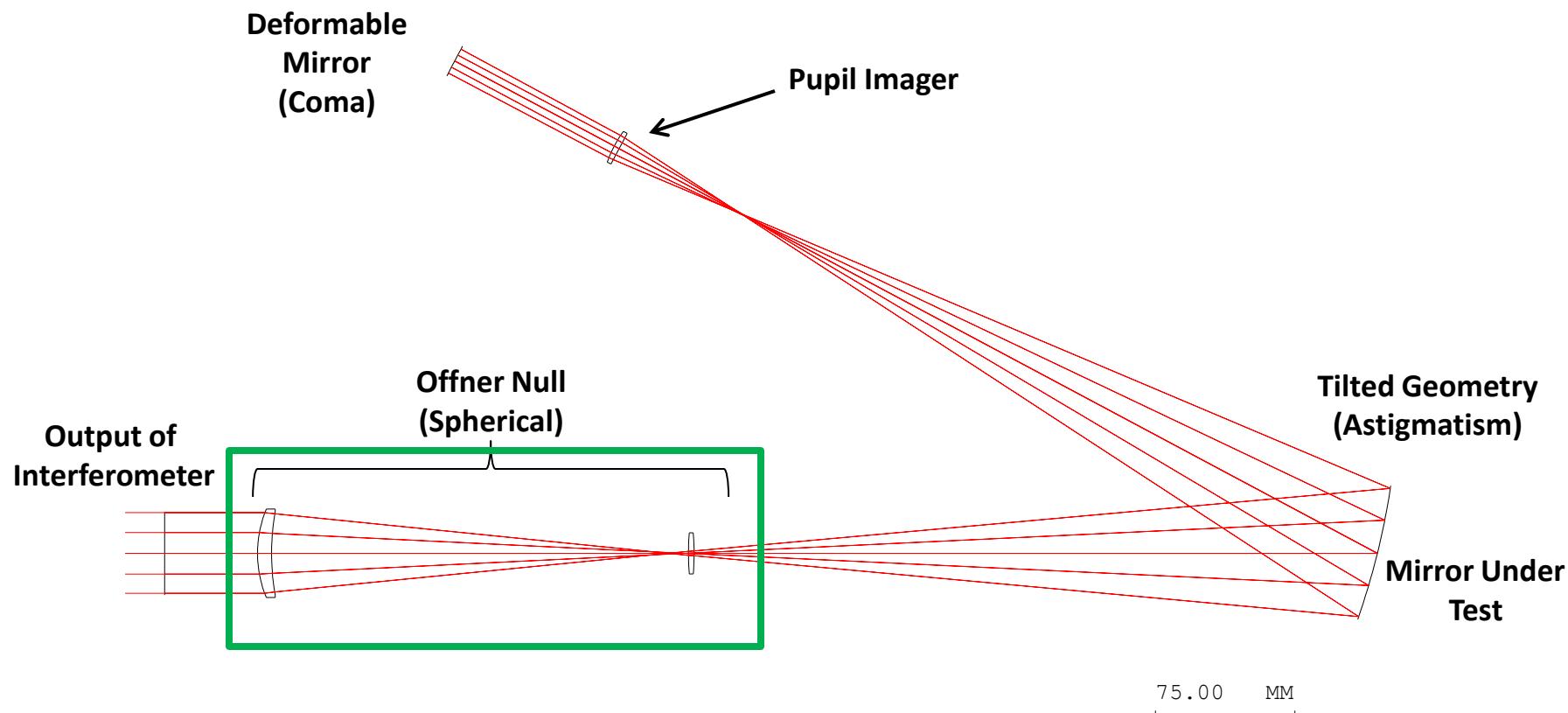
Metrology

- Acceptance testing/characterization configuration for the secondary mirror



Metrology

- Acceptance testing/characterization configuration for the secondary mirror



Summary

- ϕ -Polynomial Surfaces:
 - Allow for off-axis optical designs with high performance
 - When located at stop surface will remove field-constant contributions to the aberration function
 - When located away from stop surface will counteract field dependent aberrations
 - Can be fabricated with current technologies in the infrared
 - Testing configurations are realizable

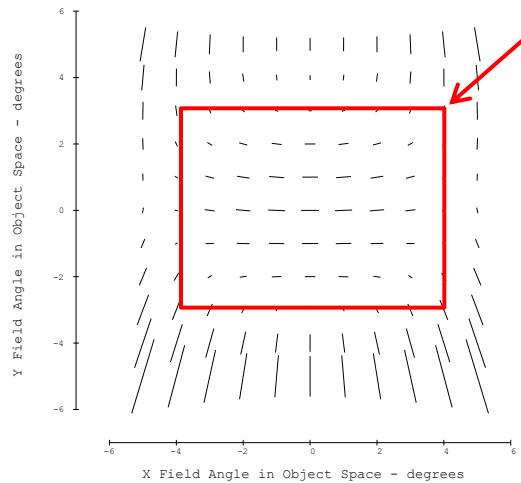
Acknowledgements

- We thank:
 - Frank J. Horton Research Fellowship
 - National Science Foundation (EECS-1002179)
 - II-VI Foundation
 - II-VI Corporation for fabrication support
 - Synopsys for the student license of CODE V

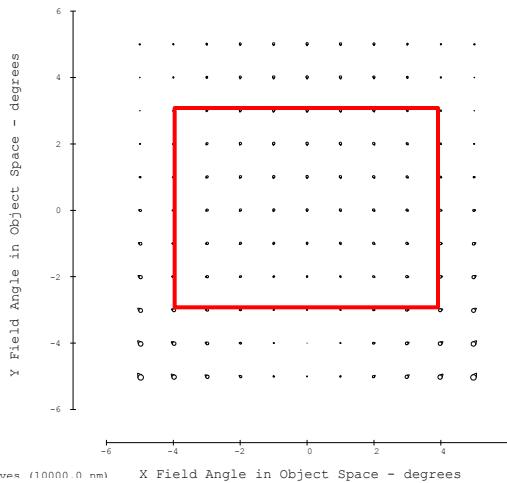
Aberrations of Final System

$Z_{\text{3rd Astig}}$

10° diagonal FFOV

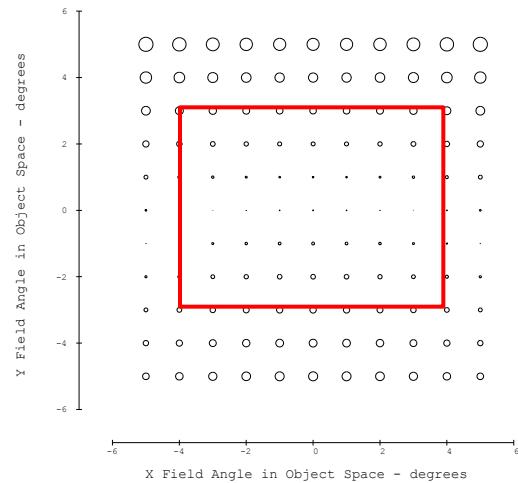


$Z_{\text{3rd Coma}}$

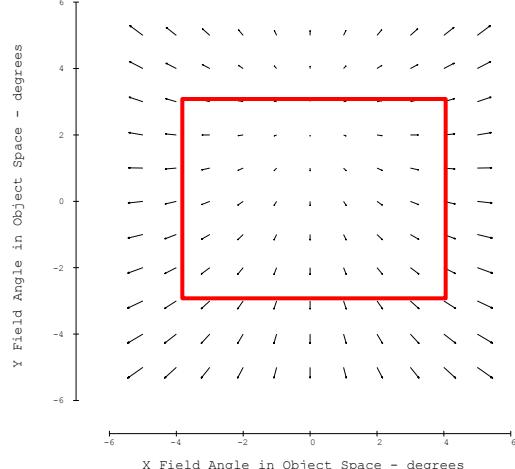


= Diffraction
Limit @ 10 μ m

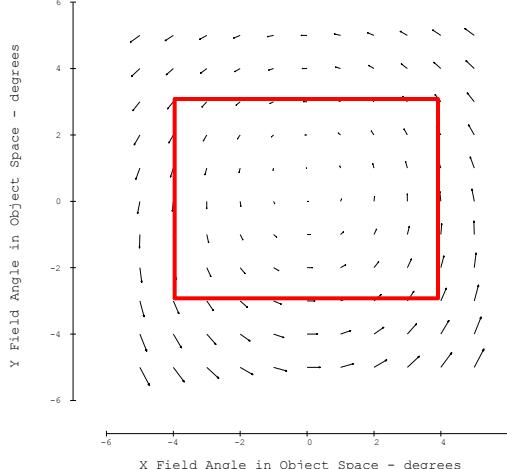
$Z_{\text{3rd Spher}}$



$Z_{\text{Ellip. Coma}}$



$Z_{\text{Obl. Spher.}}$



$Z_{\text{5th Spher}}$

